

LA-UR-13-27962

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Title: Broken Symmetry in the Pseudogap State of  $\text{YBa}_2\text{Cu}_3\text{O}_{6+x}$

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Intended for: Discussion with external collaborators

Issued: 2013-10-15



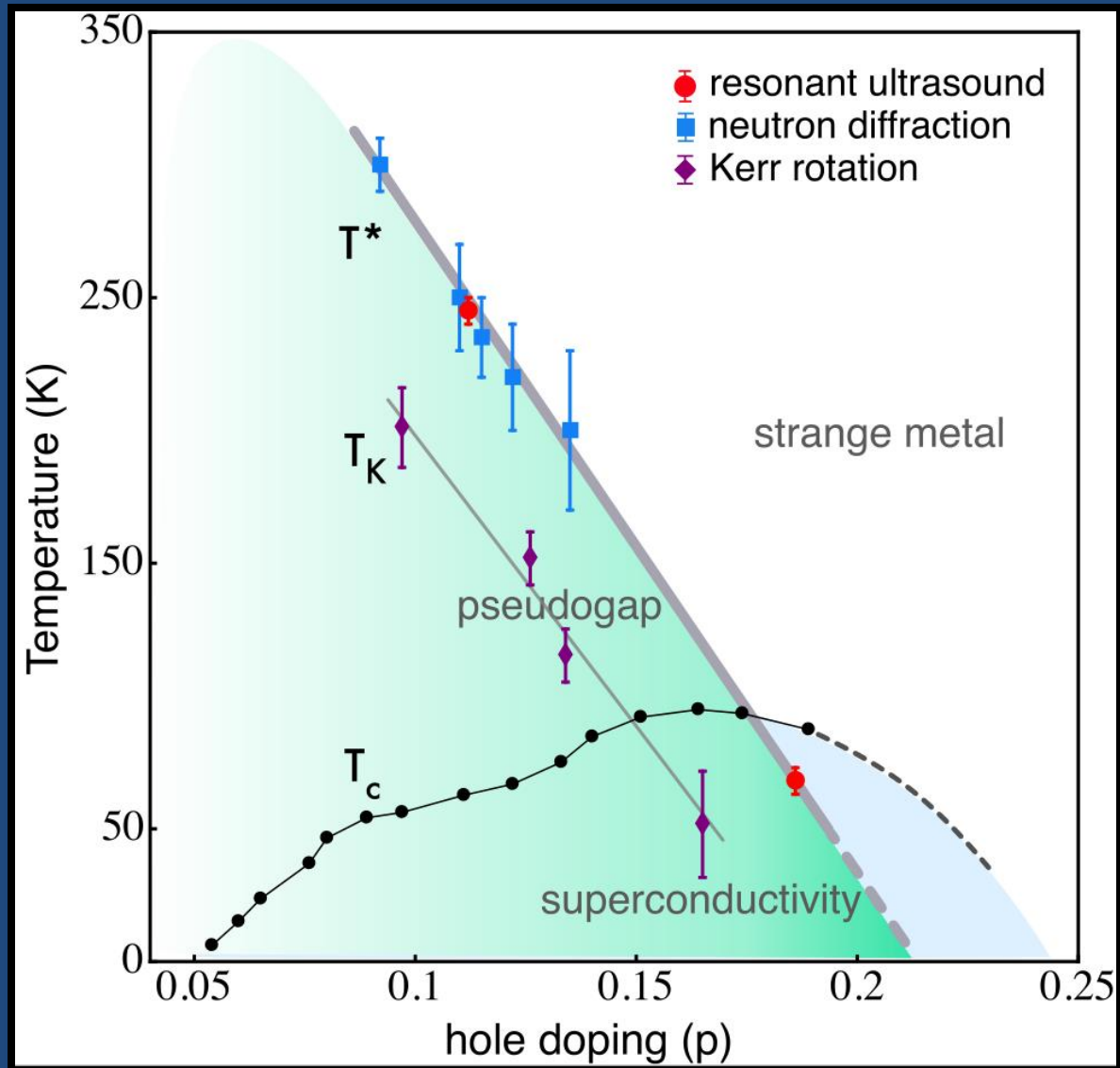
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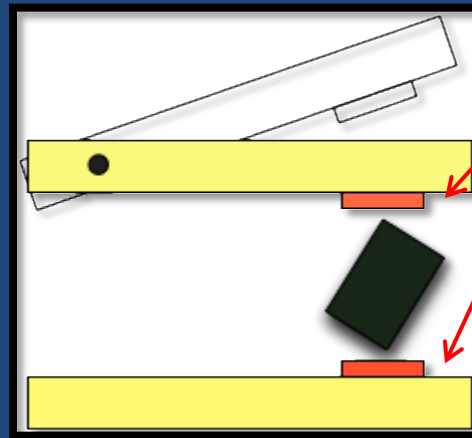
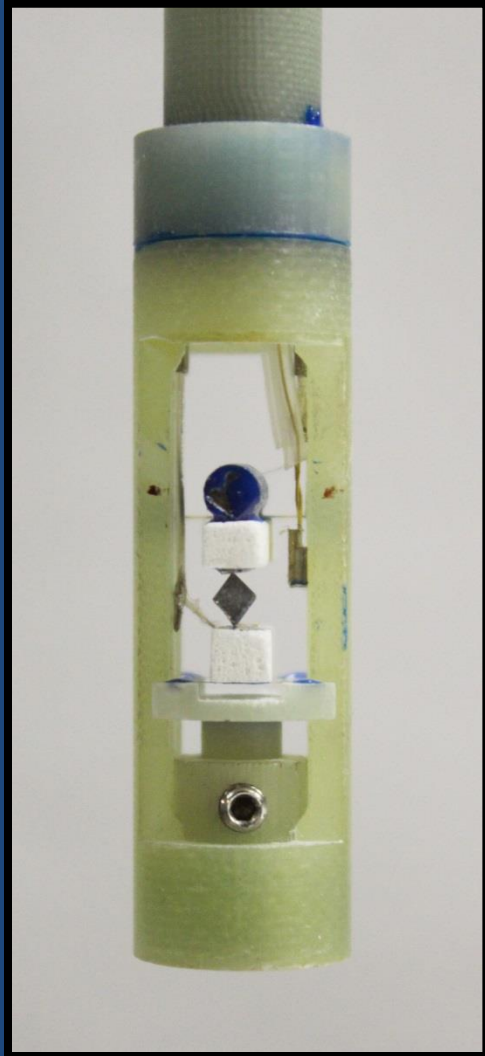
# Broken Symmetry in the Pseudogap State of $\text{YBa}_2\text{Cu}_3\text{O}_{6+x}$

Brad Ramshaw

# Pseudogap in $\text{YBa}_2\text{Cu}_3\text{O}_{6+x}$

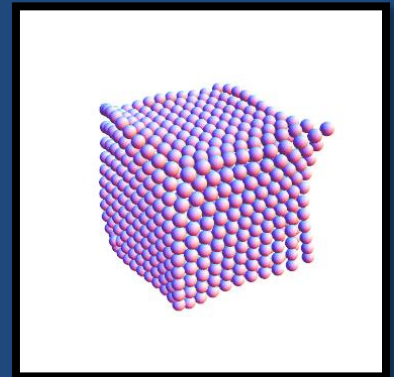
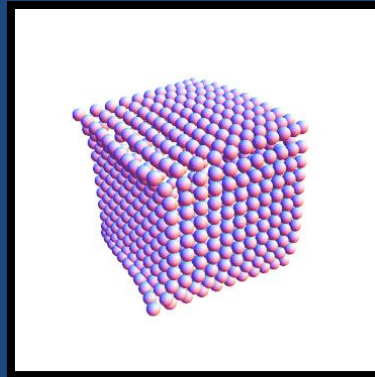
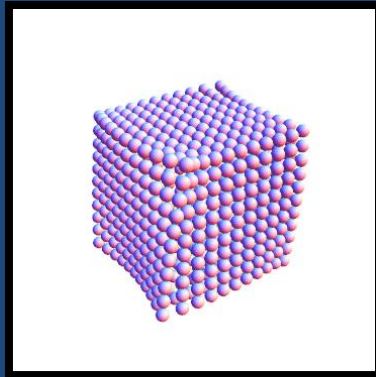
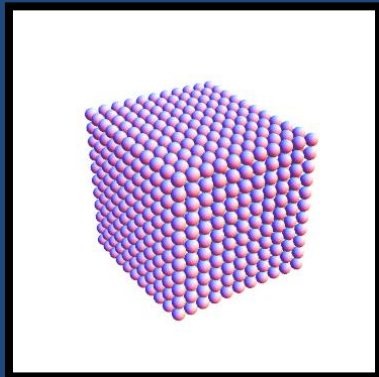
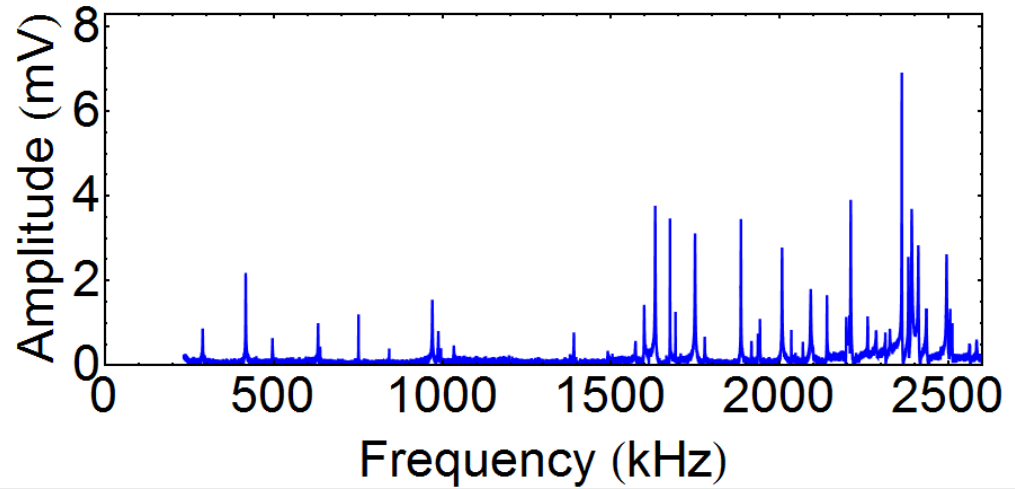
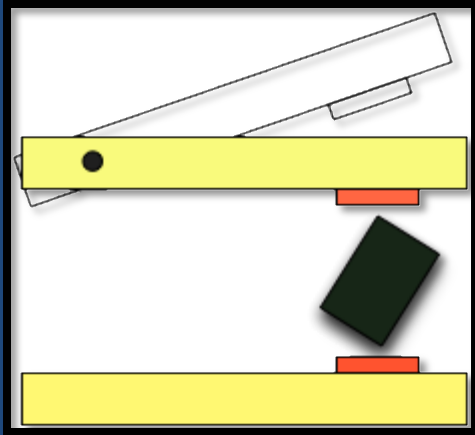


# Resonant Ultrasound Spectroscopy



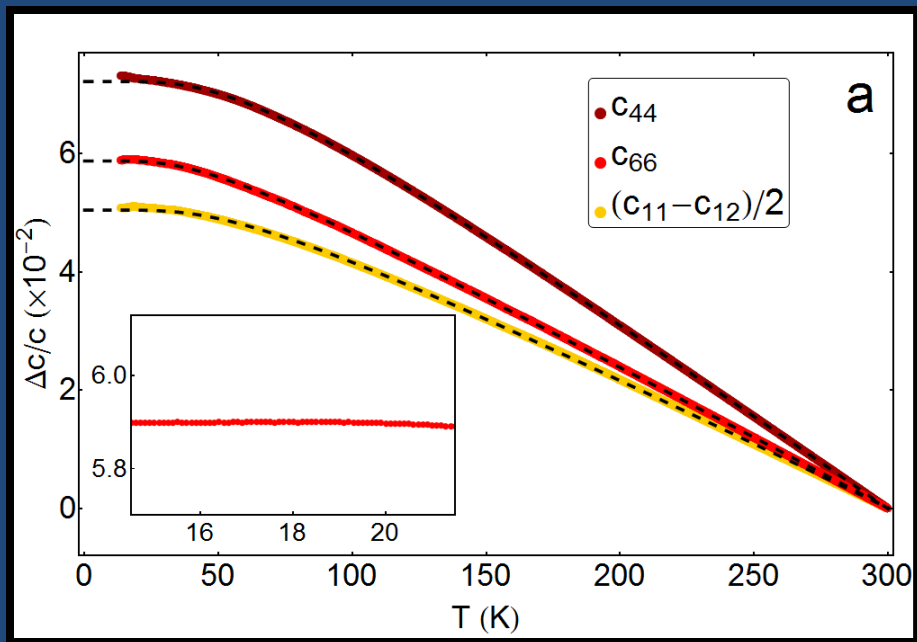
Drive at frequency  $\omega$   
Detect transmitted power

# Resonant Ultrasound Spectroscopy

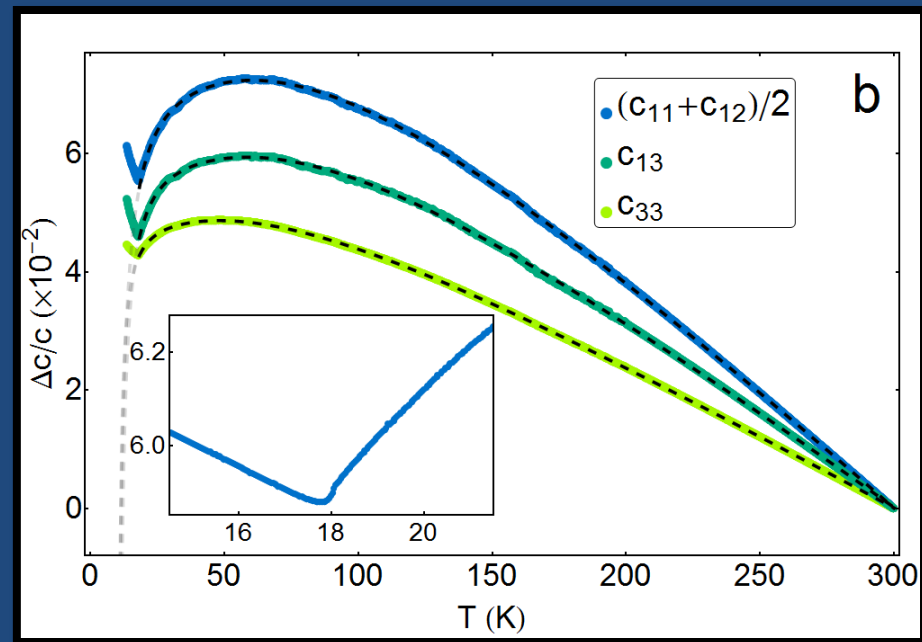


# PuCoGa<sub>5</sub>

## Shear



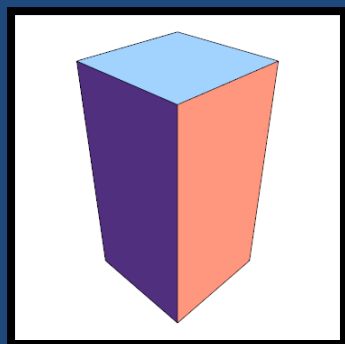
## Compression



# Strain in a Tetragonal Environment

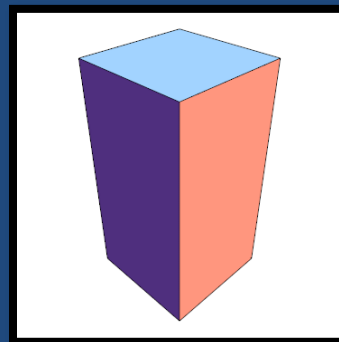
Compressional

Shear



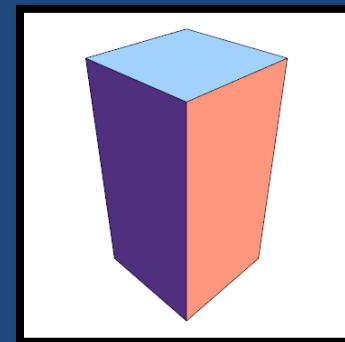
$A_{1g}$

$$(c_{11}+c_{12})/2$$



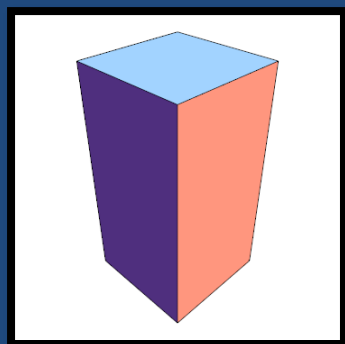
$B_{1g}$

$$(c_{11}-c_{12})/2$$



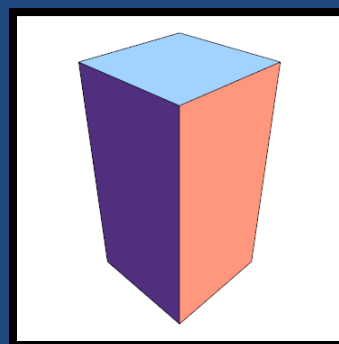
$B_{2g}$

$$c_{66}$$



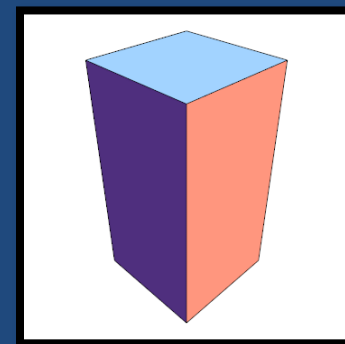
$A_{1g}$

$$c_{33}$$

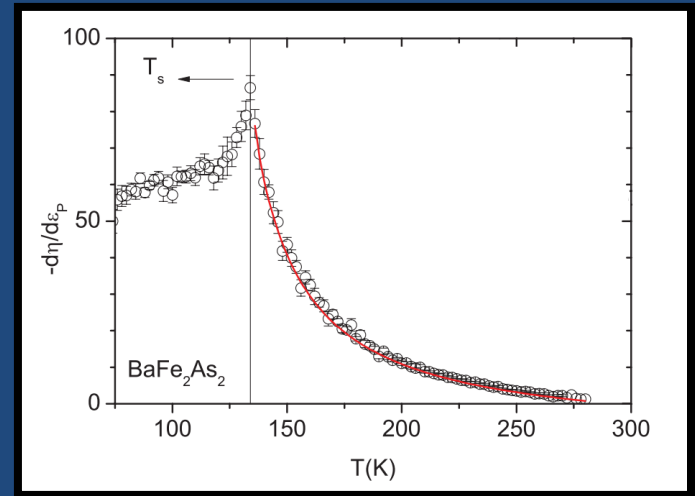
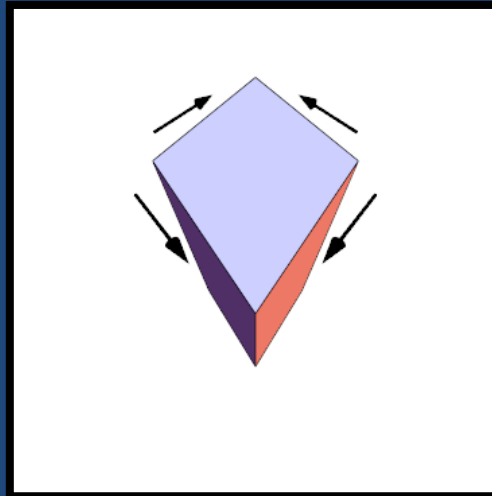
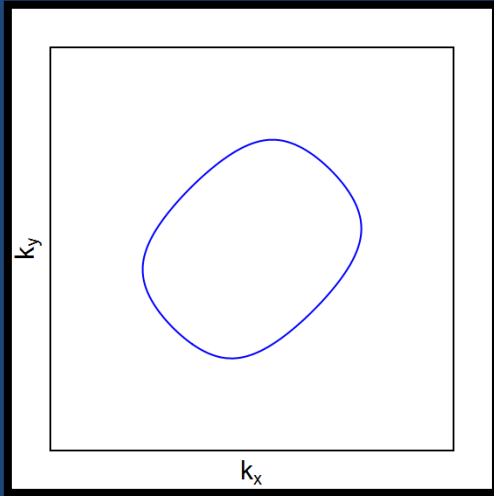


$E_g$

$$c_{44}$$



# Order Parameter Coupling



Jiun-Haw Chu *et al.* Science 337, 710 (2012)

$$c_i = \frac{\partial^2 F}{\partial \epsilon_i^2}$$

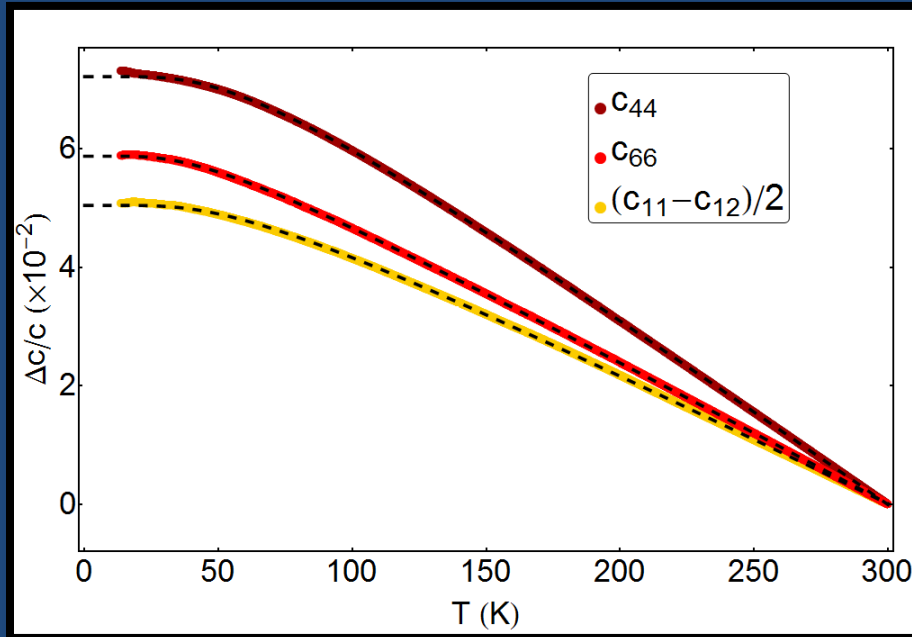
$$F = \sum_i c_i (\epsilon_i)^2 + \alpha(T - T_0)\eta^2 + \beta(\epsilon_{\underline{B2g}} \cdot \eta) + \dots$$

$$c_{B2g} \propto \frac{1}{T - T_0}$$

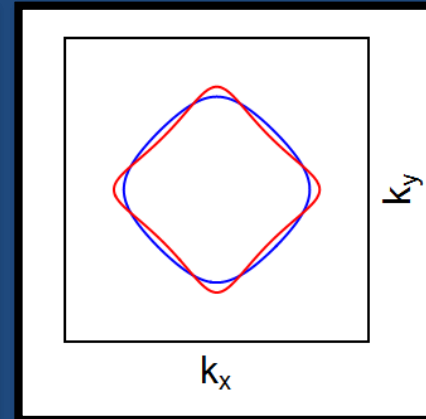
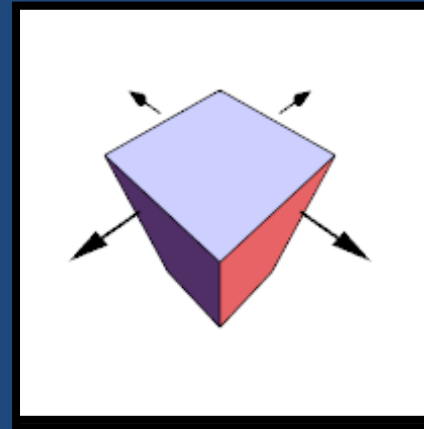
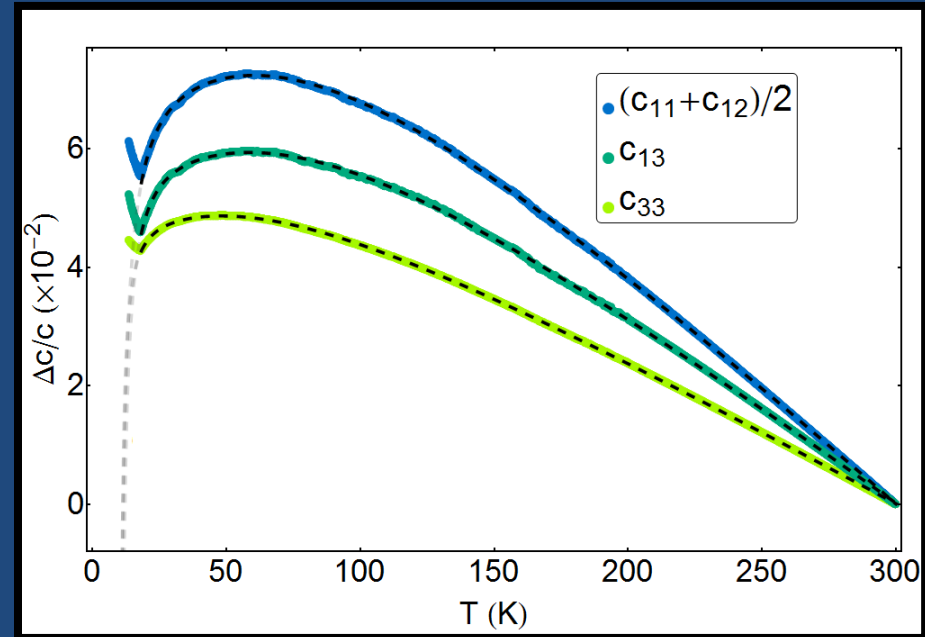


# Valence Fluctuations in PuCoGa<sub>5</sub>

## Shear

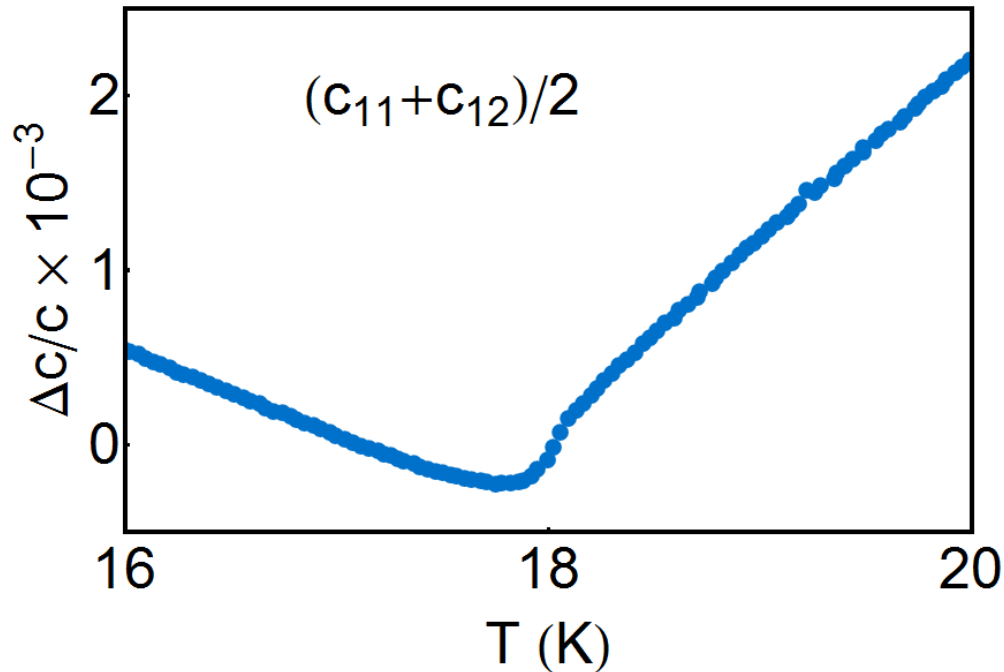


## Compression



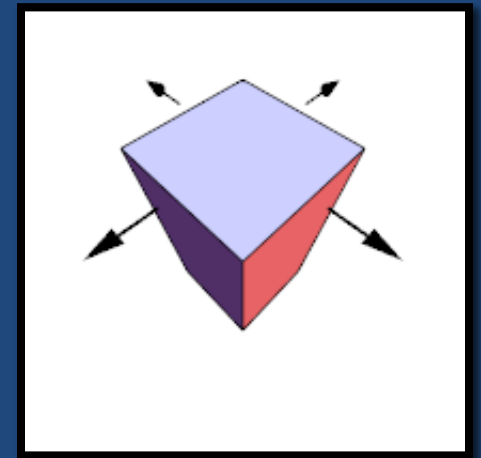
# Superconductivity in PuCoGa<sub>5</sub>

$$F = \sum_i c_i (\varepsilon_i)^2 + \alpha(T - T_c) |\psi|^2 + \gamma |\psi|^4 + \beta(\varepsilon_{A1g} \cdot |\psi|^2) + \dots$$

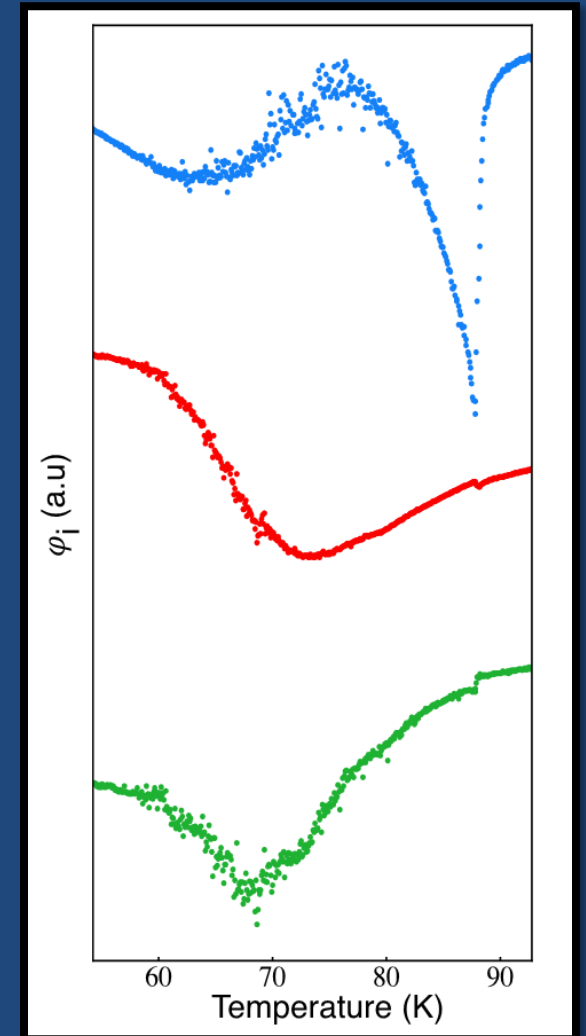
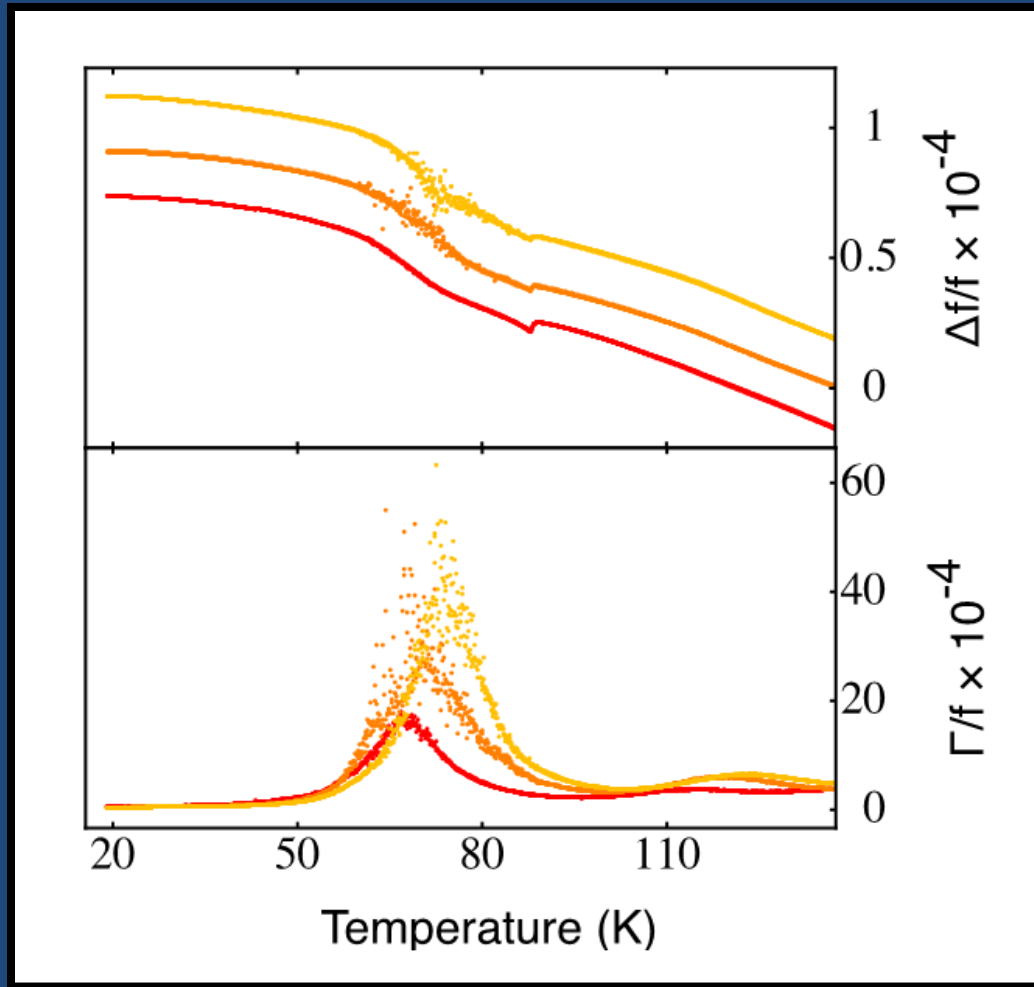


$$c_{A1g} = c_{A1g}^0 \quad T > T_c$$

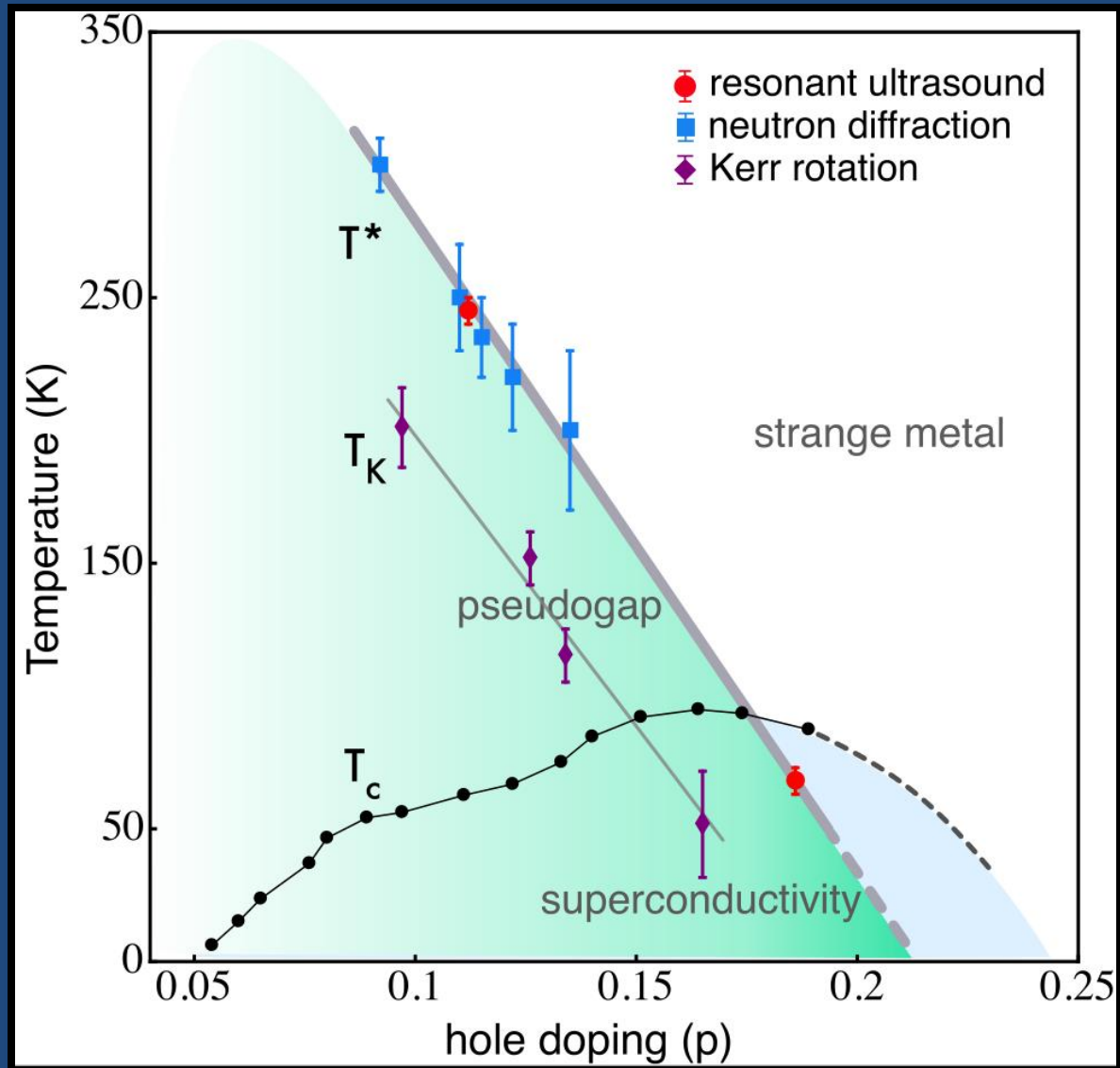
$$= c_{A1g}^0 - \frac{\beta^2}{2\gamma} \quad T < T_c$$



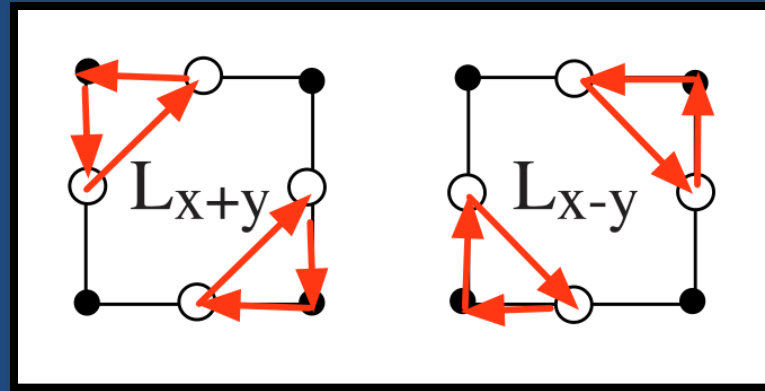
# Discontinuity at the Pseudogap in $\text{YBa}_2\text{Cu}_3\text{O}_{6+x}$



# Pseudogap in $\text{YBa}_2\text{Cu}_3\text{O}_{6+x}$



# Scenarios for the Order Parameter



Shekhter, A. *et al.* PRB 80, 214501 (2009)

$$E_u \times E_u \rightarrow A_{1g} + A_{2g} + B_{1g} + B_{2g}$$

$\downarrow$   
 $(c_{11} + c_{12})/2$   
 $c_{33}$

$\downarrow$   
 $(c_{11} - c_{12})/2$

$\downarrow$   
 $c_{66}$

All four moduli should show a discontinuity at T\*!

# Summary